THE RELATIONSHIP BETWEEN WORK TEMPO AND FORCE APPLIED IN A HORIZONTAL PLANE

A Thesis

Submitted to the Faculty

of

Purdue University

by

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In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science

in

Industrial Engineering

June 1955

ACKNOWLEDGMENTS

The writer wishes to express his thanks and appreciation to Professor H. T. Amrine for his assistance and guidance in the preparation of this thesis. He is indebted to Dr. L. J. Cote who set up the statistical procedures and directed the reduction of the data.

The writer also thanks all those who gave helpful suggestions in building the equipment and especially his friends who gave freely of their time and energy as operators.

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ABSTRACT

Gately, Donald Edward. M. S. in Industrial Engineering., Purdue University, June 1955. The Relationship Between Work Tempo and Force Applied in a Horizontal Plane. Major Professor: H. T. Amrine.

This experiment was an investigation of the relationship between work tempo and force applied (or resistance overcome) in a horizontal plane.

The apparatus used was a table with a handle protruding through a slot in the top surface. A mechanism made it possible to increase and decrease the handle's resistance to movement in one direction (it was always free to move unrestrained in the other direction).

Ten operators moved the handle back and forth at the maximum pace they could maintain for one minute and then rested for five minutes. Each operator moved the handle in four different ways, namely, standing and pushing against the resistance, standing and pulling against the resistance, sitting and pulling, and sitting and pushing. In each of these parts each operator met six different resistances ranging from two to thirty-two pounds which were presented in a random order. An electric clock was used to record the time to perform thirty cycles about halfway through each operator's stint.

The results of this investigation indicate that work tempo and force applied horizontally may be considered to

be linearly related and that there are significant differences between overcoming the resistance while standing or sitting, and between overcoming the resistance by pushing or by pulling. It was also found that the interactions between these methods are not significant.

It was concluded that, under the conditions of the experiment and for the group of operators who performed the experiment:

1. Work tempo is, within the limits of experimental error, linearly related to resistance in a horizontal plane, and decreases as the resistance is increased.
2. The work tempo, and hence the difficulty entailed in overcoming a resistance in a horizontal plane, varies as the method employed to exert the force is changed. In particular, this investigation showed that:
   a. there is a significant difference in work tempo, or difficulty, between exerting a force horizontally while standing or while sitting, with the latter being the more difficult.
   b. there is a significant difference in work tempo, or difficulty, between exerting a force horizontally by pulling or by pushing with the latter being the more difficult.

c. the interactions between sitting and standing or pulling and pushing are not significant and, hence, the effects of these changes in method may be considered additive.

3. For the four methods of overcoming resistance in a horizontal plane investigated in this experiment, sitting and pushing against the resistance was the most difficult and standing and pulling against the resistance proved the easiest.

4. A single allowance or adjustment curve applied universally to all types of work entailing the overcoming of resistance cannot be used without introducing an error into the time standard.

5. Allowances and/or adjustments to compensate for job difficulty are a function of the method employed in overcoming the resistance; hence, one universal value cannot suffice.

These findings indicate a need for further investigation of this subject using different methods of overcoming resistance in oblique planes as well as horizontal and vertical planes.

THE RELATIONSHIP BETWEEN WORK TEMPO AND FORCE APPLIED IN A HORIZONTAL PLANE

INTRODUCTION

Usually when a time study man takes a time study for use in rate setting he must decide in some manner how the performance of the worker he is observing compares with the performance of the so-called "average worker" doing the same job. This comparison is called rating and may consist of comparing such things as the performance, pace, effort or skill of the worker observed with a mental image of what is normal for that particular job. This is necessarily a subjective process and has been the basis of a great deal of the criticism time study has received.

Some practitioners in the field rate pace alone and then adjust the normal or base times with a fatigue allowance (often as high as fifty percent)[1]. Others feel that fatigue need not be considered since a modern well-managed industrial plant does not subject the workers to fatigue[2]. Lowry and his colleagues[3] ignored pace in their rating system but took note of the effort, among other factors, involved in any particular job. In an attempt to remove some of the subjectivity present in the rating process, Presgrave[4] proposed bench marks such as walking or dealing cards at prescribed rates.

Mundel[5] took the next logical step toward objectivity. He proposed that all jobs be rated on pace against a single standard of pace. These ratings are then modified by a series of secondary adjustments which compensate for job difficulty. One of these secondary adjustments is concerned with the weight or resistance which is encountered in doing the job.

As originally proposed, Mundel recommended one curve, based on Solberg's[6] work with a weighted lever, from which an adjustment could be chosen for any and all jobs. Sekerci[7] wondered about the universality of application of this one curve. He showed that the allowance necessary for lifts from the floor to waist level differed significantly from that necessary for lifts from waist to shoulder level. Such results suggest that still other allowance curves might be necessary if the weight or resistance is encountered in still different ways. Should the allowance for lifting a given weight vertically be different from moving a comparable resistance in the horizontal plane?

Physiologists in their attempts to determine the most efficient pace for given jobs have arrived at different values when the jobs entailed meeting resistances differently[8]. This further suggests that the manner in which a resistance is overcome in performing a job alters the difficulty of the job.

Job difficulty can be related to work tempo directly. As pointed out by Mundel and Radkins[9],

> ....if two tasks are identical, including the exertion level, except for one controlled variable, and these two tasks are both performed at maximum pace or maximum relative exertion, then the observed difference on time for the two tasks.....evaluates the effect of the controlled variable on job difficulty.

PURPOSE

The purpose of this experiment was to investigate the relationship between work tempo and force exerted in a horizontal plane. In addition, different methods of exerting the horizontal force were investigated to ascertain if they had any effect on the relationship between work tempo and force.

EQUIPMENT

The apparatus used in this experiment consisted of a handle connected to a device through which a variable amount of resistance to movement could be controlled. The handle moved horizontally and met no resistance to movement in one direction. In addition, an electric clock calibrated in one hundredths of a second, a standard time study stop watch, and a mechanical counter were used.

The device (Figure 1) consisted of a table through the top of which a handle protruded. The handle was attached to a cart which ran on two straight, iron tracks suspended just beneath the top of the table. The cart, in turn, by means of a pivot and a series of rollers (Figures 2 and 3), was attached to a lever connected to a ratchet. A horizontal movement of the handle and cart caused the rollers to ride along the lever turning it through an arc of approximately sixty degrees. The ratchet was attached to an axle on which was mounted a hard wood drum, four inches in diameter. A series of cables, pulleys, turnbuckles, and a spring (Figure 4) furnished a means of adjusting the pressure on a leather belt draped over the wooden drum. The net result of this arrangement was that the handle, when moved in one direction, rotated the drum against the friction of the leather belt. Movement in the other direction (i.e. returning the handle to its original position) met no

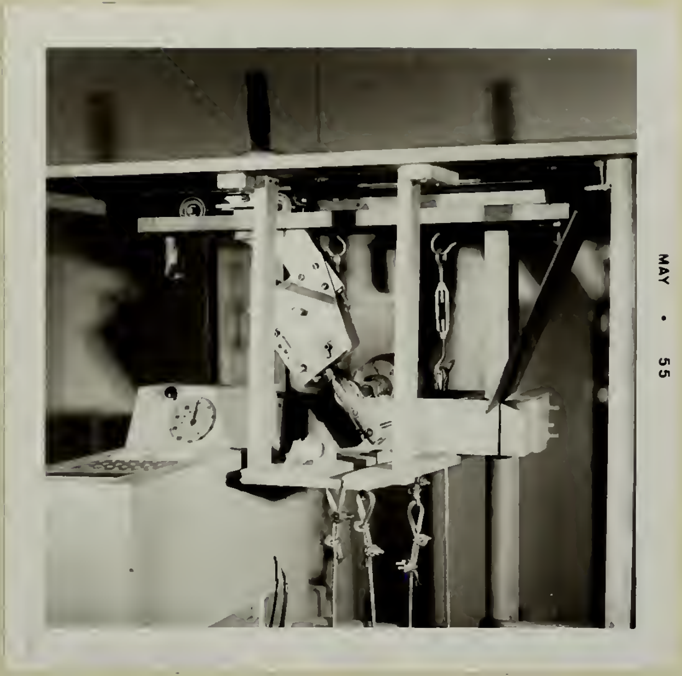

Figure 1

General view of the mechanism.

Figure 2

Close-up showing cart, lever,

ratchet and counter.

Figure 3

Close-up showing cart, lever,

and rollers.

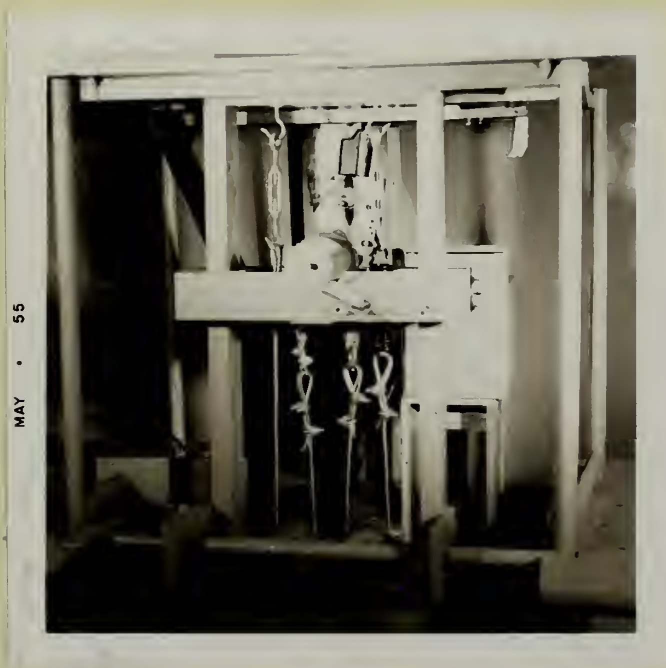

Figure 4

Cable and spring arrangement for varying friction on the wooden drum.

resistance due to the ratchet. Tightening the turnbuckles increased the tension on the belt and, as a result, the force required to move the handle.

EQUIPMENT CALIBRATION

To calibrate this device a pulley was mounted on the table top and a weight was attached to the handle (Figure 5). The tension on the belt was adjusted by turning the turnbuckle until the weight was just sufficient to move the handle slowly (after it was set in motion to overcome the greater initial static friction) with no apparent acceleration. When this condition was achieved, the turnbuckle was marked, a new weight was substituted, and the process repeated. This manner of calibrating the equipment insured that all of the friction inherent in the system as well as that artificially introduced by the belt was accounted for in the calibration.

The turnbuckles were calibrated in six positions, i.e. those tensions which required weights of 2, 4, 8, 16, 24, and 32 pounds to move the handle. After the device had been calibrated for all of the desired resistances, each value of resistance was approached from either direction several times and the value rechecked to insure that this manner of calibration allowed consistent and accurate results. The calibration was also checked between groups of operators while the experiment was being run to insure that the calibration was still correct.

A platform was constructed on either end of the table such that the distance from the platform to the

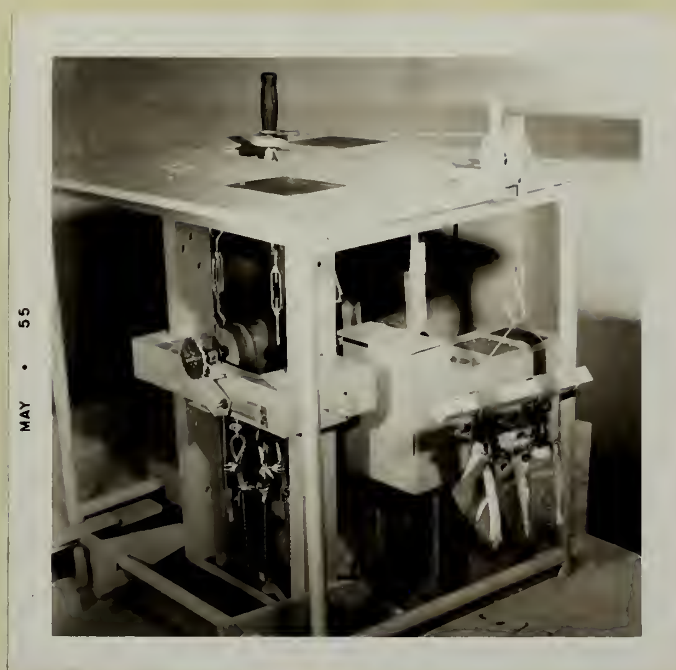

Figure 5

View showing how device was

calibrated.

bottom of the handle was thirty-six inches. This height was used since it corresponds to the average height of levers on machine tools[10] and the average height of working benches[11]. A cleat was fastened to each platform in the same relative position to the handle to hold a stool or the heels of the operator's feet. The stool was adjusted such that the distance between the top of the stool and the top of the table was nine inches which is the difference in height recommended for stand-sit work situations[12].

PROCEDURE

Ten male students, one from Turkey and the rest from the United States, acted as operators. Their ages ranged (see Table 6 in Appendix A) from twenty-three years to thirty-one years, their heights from five feet six and one half inches to six feet six inches, and their weights from one hundred sixty-five to two hundred thirty pounds. The other personal characteristics recorded are shown in Table 6. All operators were right-handed.

There were four parts to this investigation, namely:
I - Standing and pushing against the resistance (Figure 6),
II - Standing and pulling against the resistance (Figure 7),
III - Sitting and pulling against the resistance (Figure 8),
IV - Sitting and pushing against the resistance (Figure 9).
As may be seen in the figures, the operator was asked in each of the standing parts to place his heels against a cleat perpendicular to the handle's travel and to place his left hand on a plate six inches by eight inches on the top of the table and to the left of the handle (see Figure 5). For the two seated portions of the experiment the operator was asked to place his heels on the rung of the stool and his left hand in his lap.

Each operator encountered six different resistances in each part of the experiment. These resistances were as follows: 2, 4, 8, 16, 24, and 32 pounds. The operators moved the handle a distance of 17 inches overcoming

Figure 6

Operator at end of stroke in
Part I (standing and pushing).

Figure 7

Operator at start of stroke
in Part II (Standing and Pulling).

Figure 8

Operator in mid-stroke in
Part III (Sitting and Pulling).

Figure 9

Operator at start of stroke

in Part IV (Sitting and Pushing).

these resistances. Each operator met the six resistances in all four different ways during one work period ranging from two and one-half to three hours in length.

At the beginning of each work period each operator was given the following instructions to read:

> This experiment, in which you are taking part, is intended to ascertain if there is a relationship between work tempo and force exerted in a horizontal plane. The handle which you will move will offer resistance to movement in one direction but will be free to move in the opposite direction. The amount of this resistance will take on six different values. The order of the resistances that you will meet is arranged according to a random sampling plan.
>
> This procedure will be repeated four times using different muscle groups.
>
> You will move the handle to and fro insuring that you touch the stops at both ends. You are asked to repeat this action at the MAXIMUM pace that you feel you can MAINTAIN for one minute. Before you start the next phase of the experiment you will have a rest period of five minutes.
>
> I will be glad to answer any questions you may have concerning the set-up, the method, or the experiment.
>
> Before we begin I will show you the right method. You may have about one minute in which to practice. After that it is requested that you rest until called for your portion of the experiment.
>
> Thank you very much for your cooperation.

Next, each operator was shown the proper stances, both standing and sitting. The equipment was adjusted to supply an eight pound resistance to the handle and each operator was allowed to pull the handle from a standing position and to push the handle from a sitting position for the allotted practice period. After this practice the operators were given five minutes to rest before the experiment commenced.

During each work period two operators worked alternately. The schedule consisted of one operator's working for one minute and then resting for five. In the two minutes which elapsed after the first operator stopped working, the equipment was readied for the second operator. This man then worked for one minute and stopped for rest. This procedure left two more mirutes to prepare the equipment for the first operator again before his five minute rest period was up. Occasionally, more than five minutes was allowed between the different parts of the experiment.

The order in which each operator met the four parts of the experiment was randomized as was the order in which the resistances were presented in each part. The operators were not informed of the pound value of the resistances during the experiment.

During each work stint for each operator the total number of cycles performed during the minute was recorded. Starting approximately fifteen seconds after the man commenced working, the time taken to perform thirty cycles was recorded. In ten cases the number of cycles timed differed slightly from thirty but, since the data was reduced to time per cycle, this slight discrepancy was considered of no consequence.

RESULTS

The time per cycle taken by each operator at the various resistances is shown in Tables 1 through 4. The mean time per cycle for each of these resistances is given as well.

Figure 10 shows the data points (means of those for all ten operators) for Part I and the curve which was fitted to these points. Similarly, Figure 11 shows the average points and the fitted curve for Part II, Figure 12 the points and the fitted curve for Part III, and Figure 13 the points and the fitted curve for Part IV. These curves, as calculated, are parallel but distinct.

Using the fitted curves, percent allowance curves were computed for each of the four parts. Table 5 shows the calculated times per cycle and the percent time allowance for Parts I through IV. Figures 14 through 17 show the allowance curves (i.e. a plot of the percent increase in time over that for two pounds resistance versus the value of the resistance) for Parts I through IV.

In order to allow a direct comparison with the curves developed by Solberg[13] and Sekerci[14], their allowance curves are shown superimposed together with the percent allowance curves developed for each part of this investigation in Figure 18. It should be noted that the data used to draw Solberg's curve were converted to a base of two pounds which was the base used by Sekerci and used in computing the curves developed in this experiment.

TABLE 1

TIME PER CYCLE (SECONDS) TAKEN AT

VARIOUS VALUES OF RESISTANCE

PART I

(STANDING AND PUSHING)

OPERATOR NUMBER	RESISTANCE IN POUNDS 2	4	8	16	24	32
1	.56793	.69433	.62733	.64483	.65166	.86633
2	.57266	.66900	.66166	.83166	.69250	.80766
3	.54496	.53876	.56873	.67520	.66523	.82896
4	.57390	.50500	.56706	.61743	.68786	.99816
5	.49253	.49813	.63970	.75650	.75580	.79823
6	.51806	.57746	.55930	.61286	.62256	.61076
7	.49850	.72340	.64393	.70633	.71096	.80930
8	.46016	.72380	.82023	.79166	.95993	1.12316
9	.51170	.48860	.60386	.63840	.60743	.72620
10	.50510	.49443	.55080	.55676	.58376	.62916
MEAN	.520950	.601291	.624260	.683163	.693769	.819792

TABLE 2

TIME PER CYCLE (SECONDS) TAKEN AT

VARIOUS VALUES OF RESISTANCE

PART II

(STANDING AND PULLING)

	RESISTANCE IN POUNDS					
OPERATOR NUMBER	2	4	8	16	24	32
1	.55216	.54962	.54990	.60833	.62166	1.03900
2	.57200	.58783	.66950	.66900	.71350	.72916
3	.54683	.61860	.61066	.64590	.65400	.66373
4	.49653	.51186	.52663	.53433	.60766	.68923
5	.50823	.52933	.56266	.53526	.57550	.67746
6	.57250	.60340	.57537	.59726	.64630	.71270
7	.48873	.45180	.51273	.54920	.54920	.59900
8	.48110	.52003	.69280	.78836	.69476	.71416
9	.46960	.52680	.52496	.60193	.52386	.68130
10	.48370	.52783	.54670	.57183	.53776	.76463
MEAN	.517138	.542710	.577191	.610140	.612420	.727037

TABLE 3

TIME PER CYCLE (SECONDS) TAKEN AT

VARIOUS VALUES OF RESISTANCE

PART III

(SITTING AND PULLING)

RESISTANCE IN POUNDS

OPERATOR NUMBER	2	4	8	16	24	32
1	.60012	.56566	.56806	.63243	.65033	.72716
2	.63066	.60810	.63600	.71006	.71533	.79433
3	.51773	.57876	.57693	.62966	.60760	.68273
4	.57613	.55280	.54923	.58810	.63586	.67500
5	.57290	.59773	.63293	.72343	.66156	.67993
6	.65863	.63376	.78920	.70793	.82990	.89676
7	.54523	.55753	.64080	.65637	.70806	.77166
8	.54480	.74120	.70423	.77983	.84536	.90983
9	.55533	.55530	.58133	.63723	.68556	.85980
10	.56756	.62296	.61610	.62713	.68993	.75486
MEAN	.576909	.601380	.629481	.669217	.702949	.775206

TABLE 4

TIME PER CYCLE (SECONDS) TAKEN AT
VARIOUS VALUES OF RESISTANCE

PART IV
(SITTING AND PUSHING)

	RESISTANCE IN POUNDS					
OPERATOR NUMBER	2	4	8	16	24	32
1	.59000	.68733	.68923	.74666	.77850	.97800
2	.61516	.67100	.74833	.80116	.82626	.97566
3	.62793	.59570	.69570	.64500	.85343	.75736
4	.62153	.66054	.69290	.71500	.70040	.81940
5	.59450	.66200	.66073	.72910	.91240	.79810
6	.58620	.58780	.62966	.65786	.72516	.73230
7	.59106	.65520	.70686	.77243	.69240	.93913
8	.69553	.67346	.97663	.94443	1.00093	1.24590
9	.59553	.62080	.89820	.68731	.72546	.80080
10	.57026	.56186	.60303	.77966	.67096	.66740
MEAN	.608770	.637569	.720127	.747861	.788590	.871405

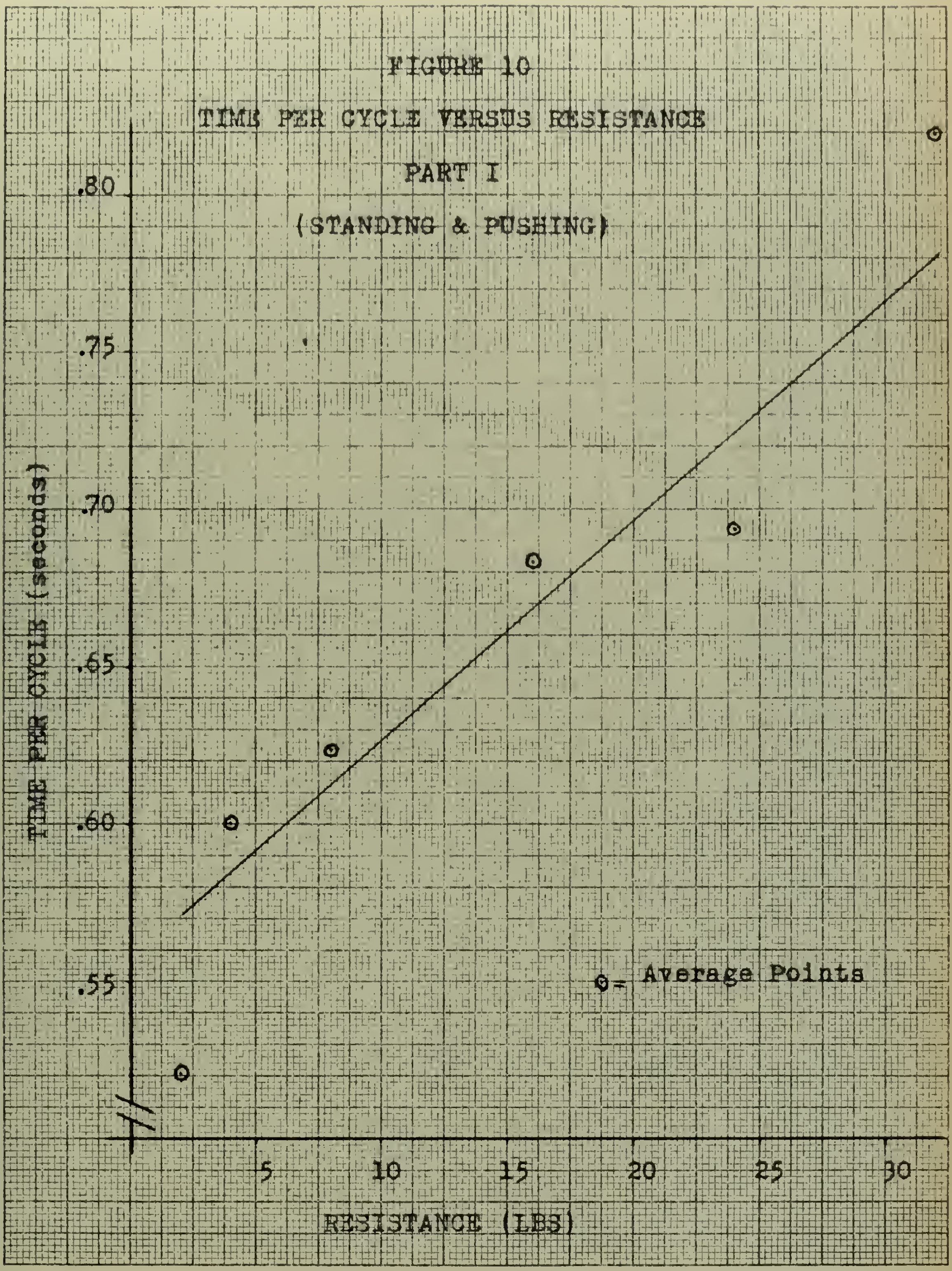
FIGURE 10
TIME PER CYCLE VERSUS RESISTANCE
PART I
(STANDING & PUSHING)
.80
.75
.70
.65
.60
.55
TIME PER CYCLE (seconds)
⊙= Average Points
5
10
15
20
25
30
RESISTANCE (LBS)

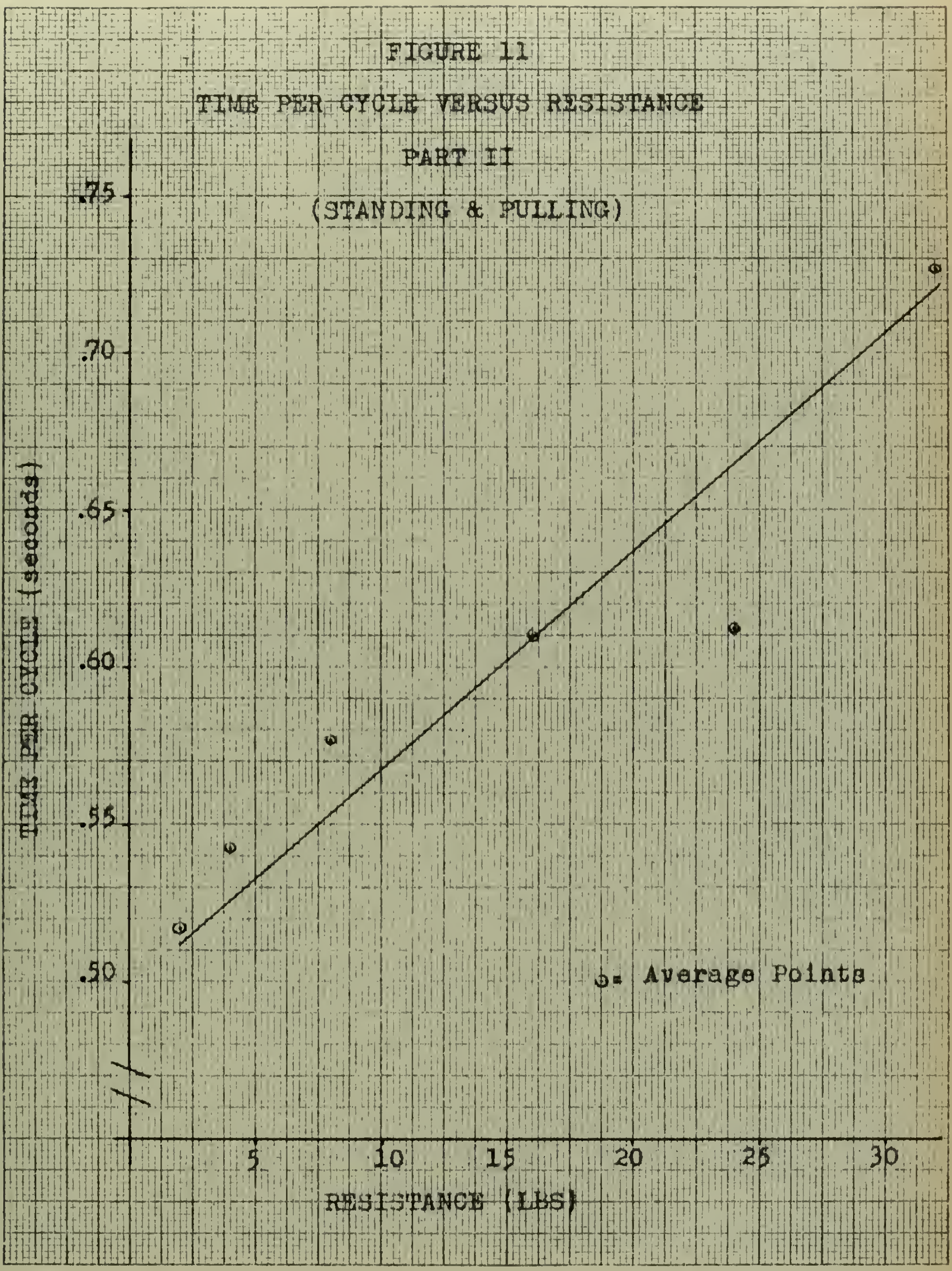
FIGURE 11
TIME PER CYCLE VERSUS RESISTANCE
PART II
(STANDING & PULLING)
TIME PER CYCLE (seconds)
.75
.70
.65
.60
.55
.50
= Average Points
5
10
15
20
25
30
RESISTANCE (LBS)

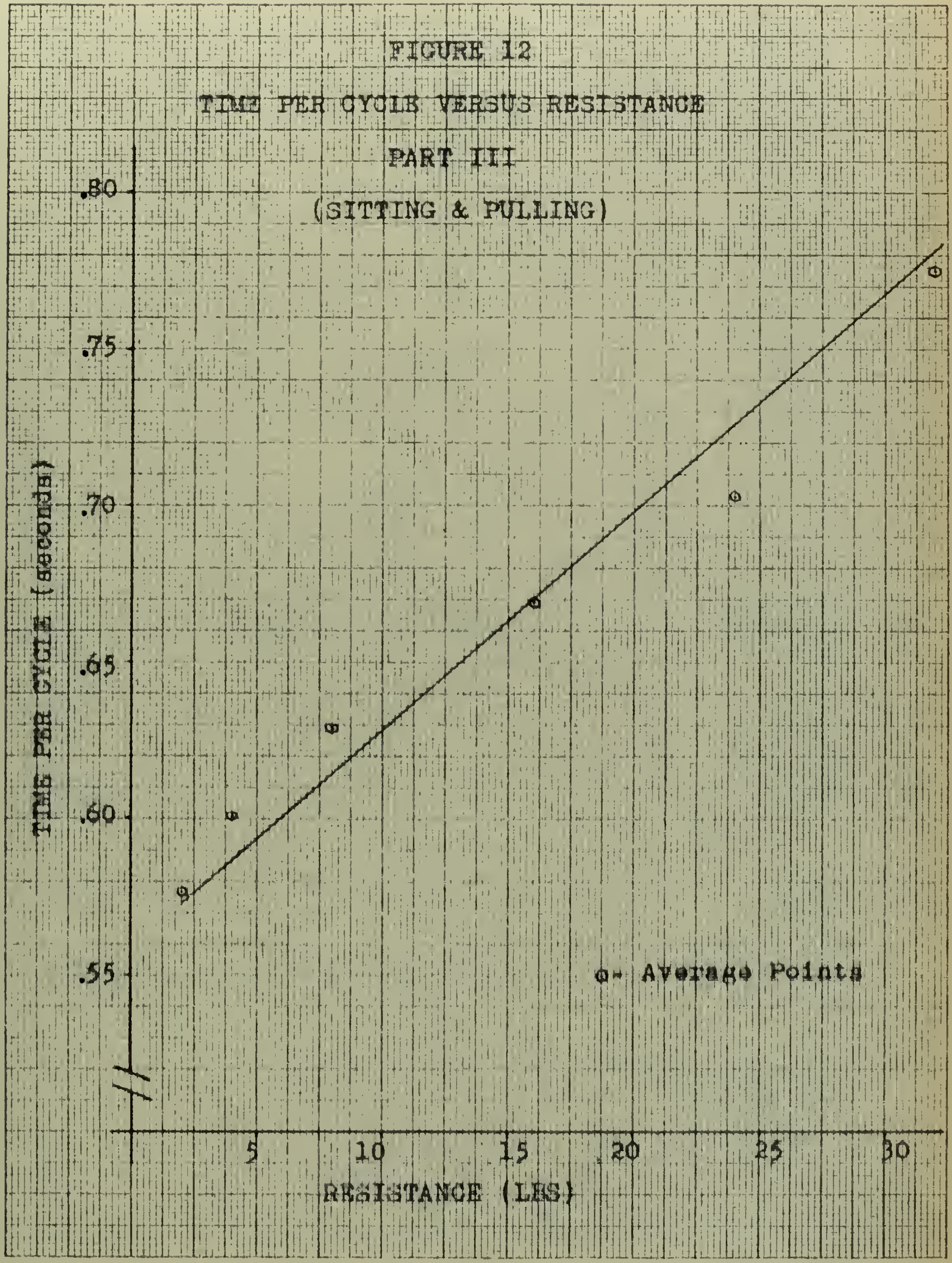
FIGURE 12
TIME PER CYCLE VERSUS RESISTANCE
PART III
(SITTING & PULLING)
TIME PER CYCLE (seconds)
.80
.75
.70
.65
.60
.55
o- Average Points
5
10
15
20
25
30
RESISTANCE (LBS)

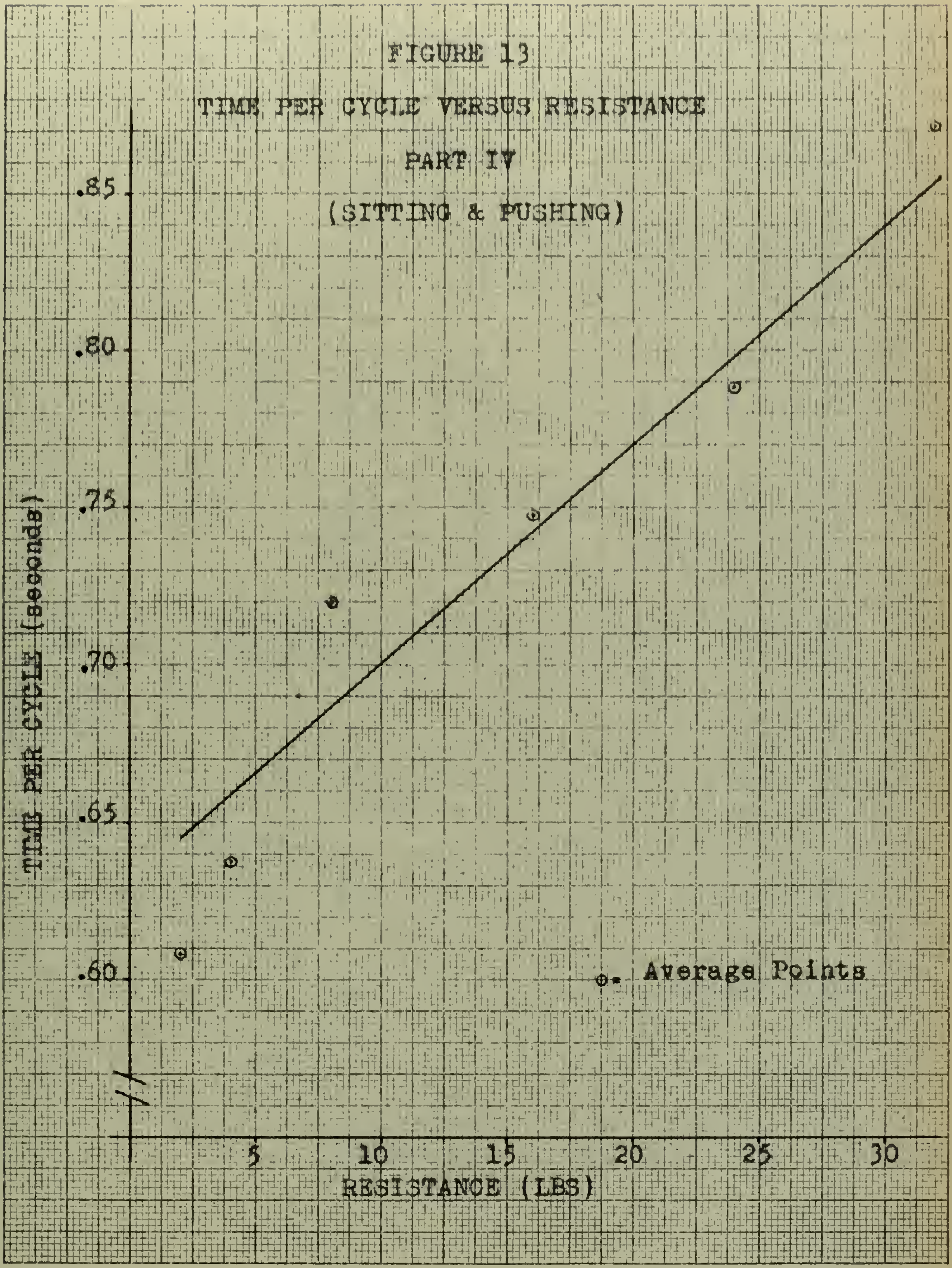
FIGURE 13
TIME PER CYCLE VERSUS RESISTANCE
PART IV
(SITTING & PUSHING)
.85
.80
.75
.70
.65
.60
TIME PER CYCLE (seconds)
⊙ - Average Points
5
10
15
20
25
30
RESISTANCE (LBS)

TABLE 5

CALCULATED TIMES PER CYCLE AND PERCENT TIME ALLOWANCES*

	PART I STANDING AND PUSHING		PART II STANDING AND PULLING		PART III SITTING AND PULLING		PART IV SITTING AND PUSHING	
RESISTANCE (lbs)	TIME/CYC. (SEC)	PERCENT ALLOW.	TIME/CYC. (SEC)	PERCENT ALLOW.	TIME/CYC. (SEC)	PERCENT ALLOW.	TIME/CYC. (SEC)	PERCENT ALLOW.
2	.571	-	.512	-	.573	-	.645	-
5	.592	3.66	.533	4.08	.594	3.65	.666	3.24
10	.627	9.76	.568	10.89	.629	9.72	.701	8.64
15	.662	15.85	.602	17.69	.664	15.80	.735	14.04
20	.697	21.95	.637	24.50	.699	21.87	.770	19.45
25	.732	28.05	.672	31.30	.733	27.95	.805	24.85
30	.766	34.14	.707	38.11	.768	34.02	.840	30.25

(Calculated times derived from the fitted curves for each part of the experiment).

$$\text{* PERCENT TIME ALLOWANCE} = \frac{\text{TIME PER CYCLE AT X lbs.} - \text{TIME PER CYCLE AT 2 lbs.}}{\text{TIME PER CYCLE AT 2 lbs.}}$$

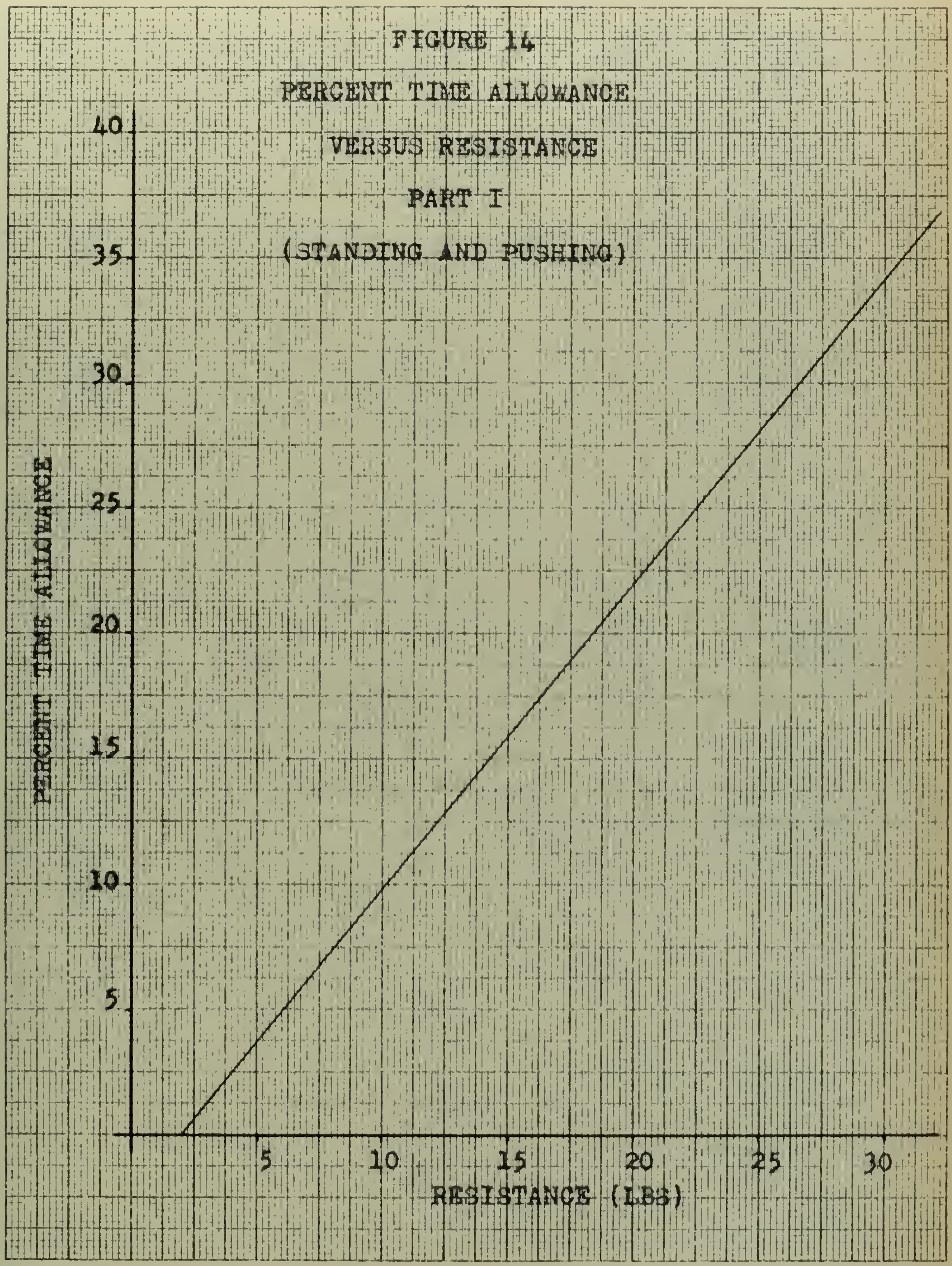
FIGURE 14
PERCENT TIME ALLOWANCE
VERSUS RESISTANCE
PART I
(STANDING AND PUSHING)
PERCENT TIME ALLOWANCE
40
35
30
25
20
15
10
5
5
10
15
20
25
30
RESISTANCE (LBS)

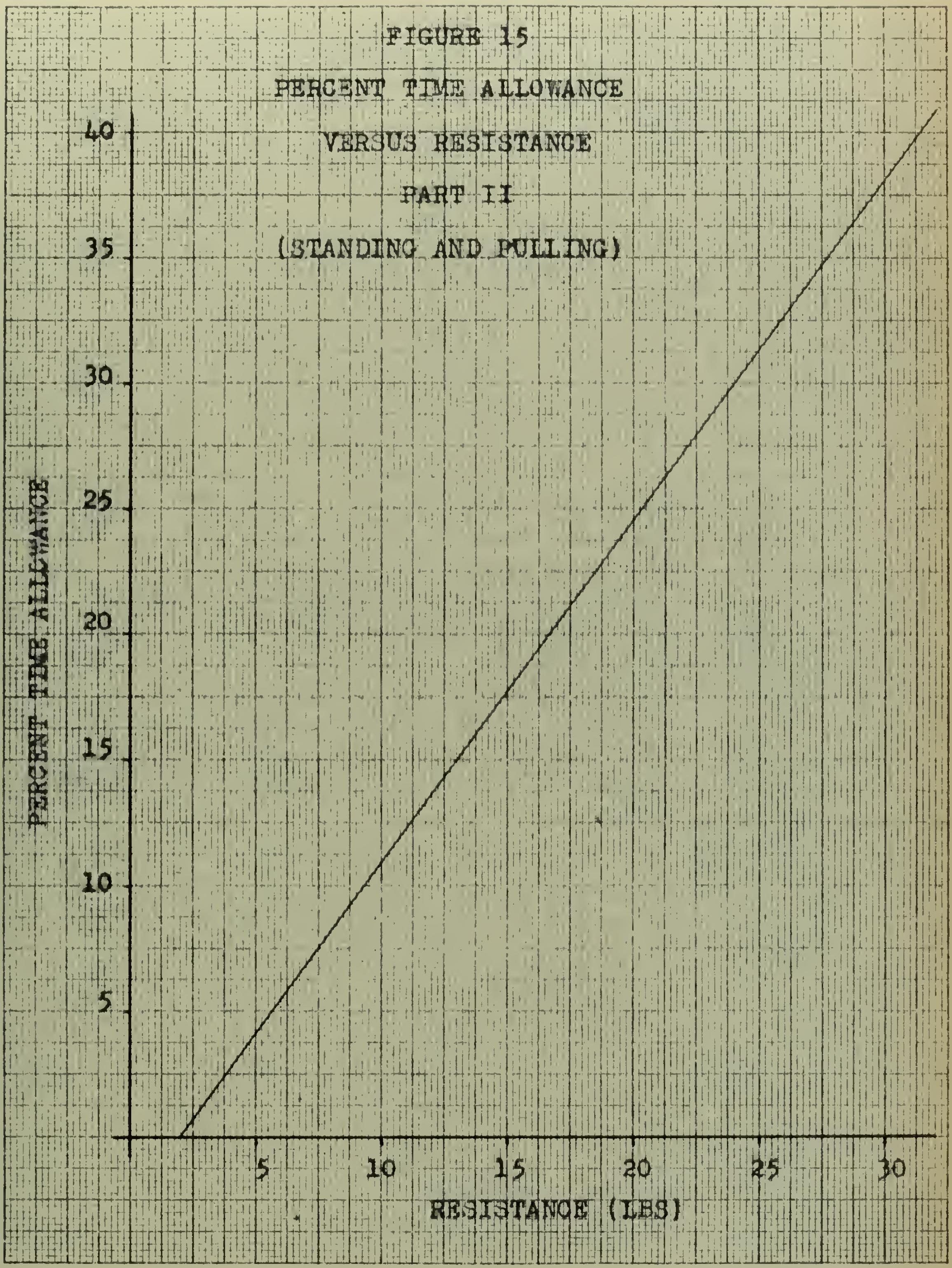
FIGURE 15
PERCENT TIME ALLOWANCE
VERSUS RESISTANCE
PART II
(STANDING AND PULLING)
PERCENT TIME ALLOWANCE
40
35
30
25
20
15
10
5
5
10
15
20
25
30
RESISTANCE (LBS)

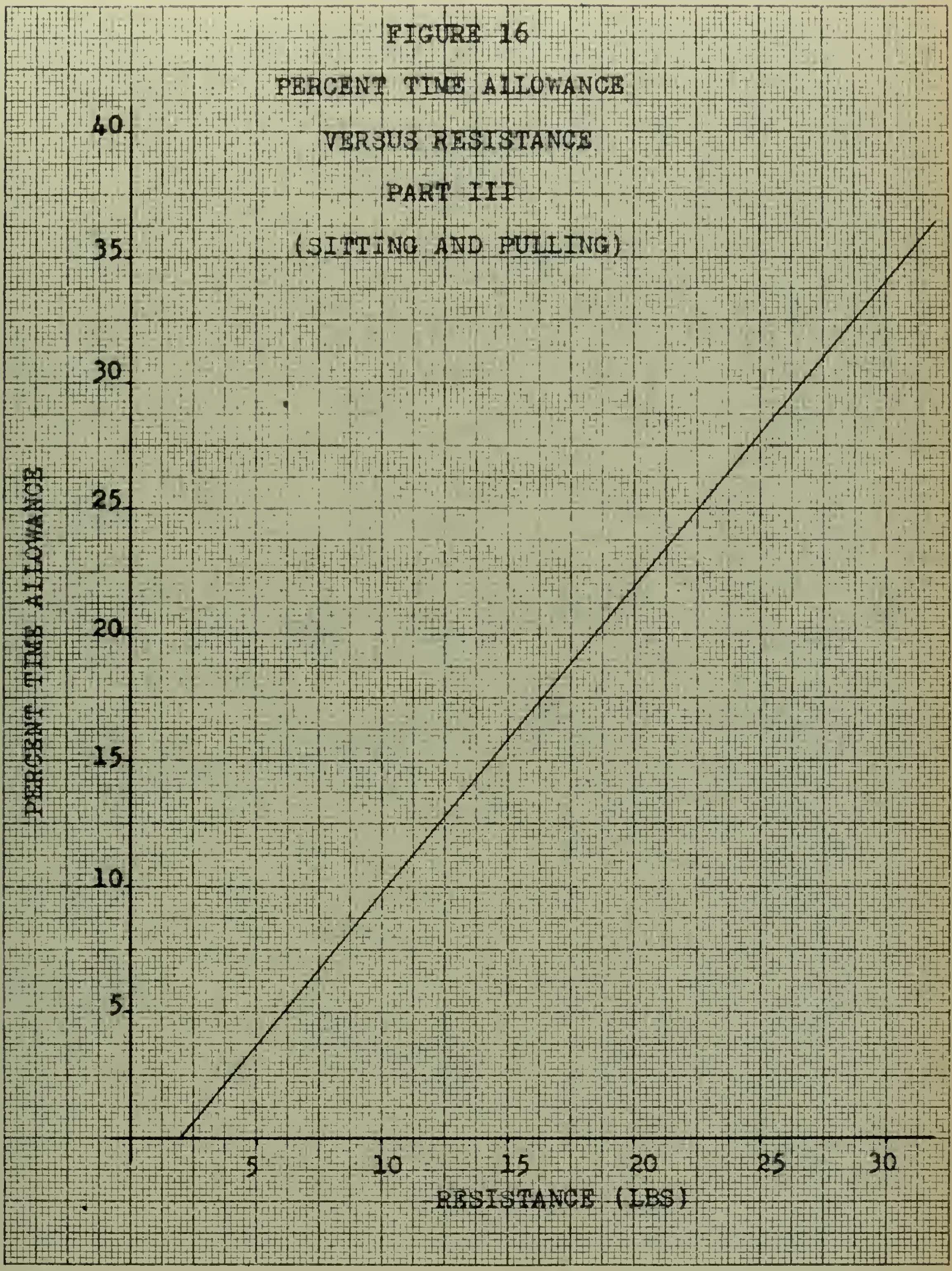
FIGURE 16
PERCENT TIME ALLOWANCE
VERSUS RESISTANCE
PART III
(SITTING AND PULLING)
PERCENT TIME ALLOWANCE
RESISTANCE (LBS)
40
35
30
25
20
15
10
5
5
10
15
20
25
30

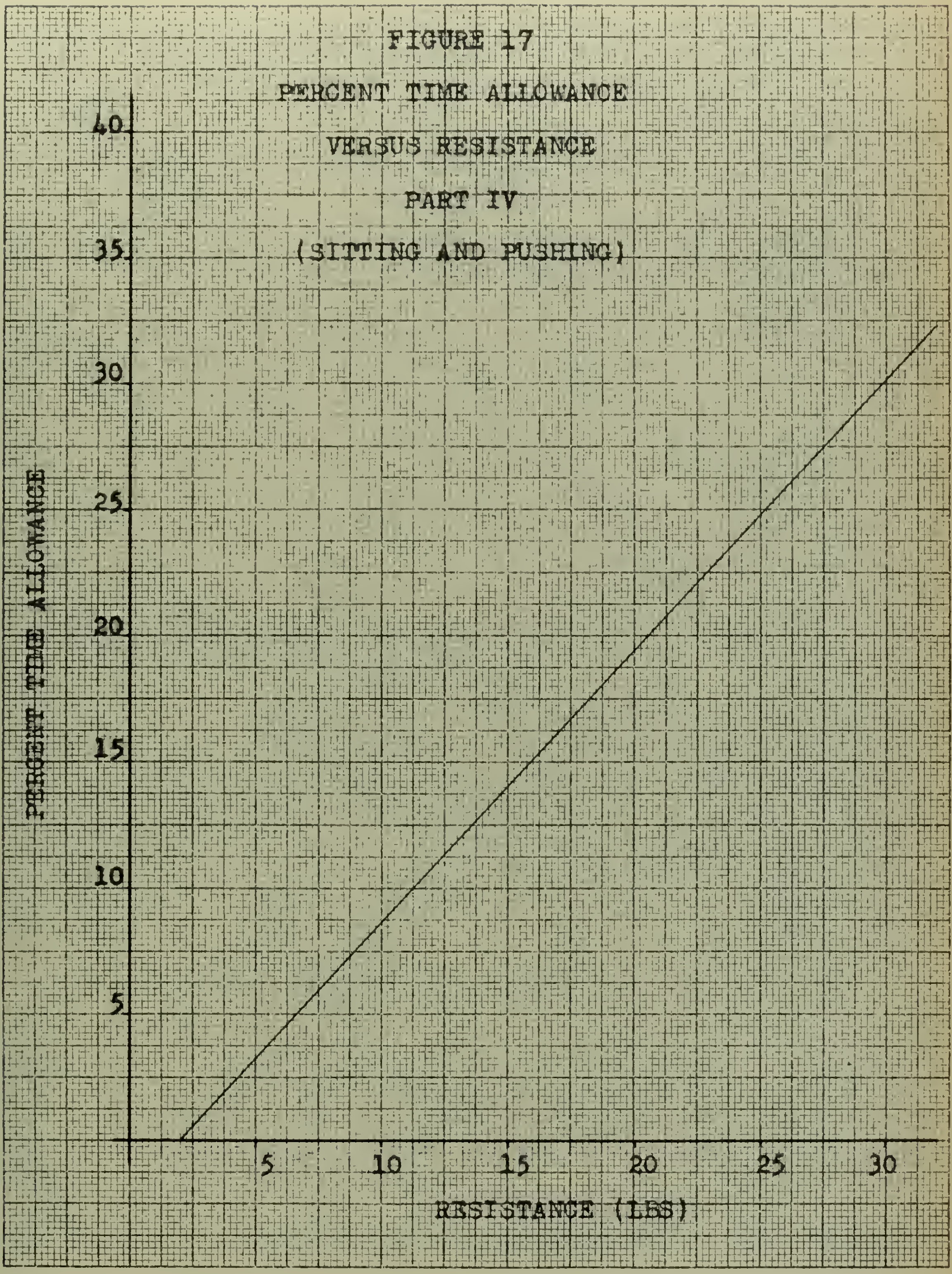
FIGURE 17
PERCENT TIME ALLOWANCE
VERSUS RESISTANCE
PART IV
(SITTING AND PUSHING)
PERCENT TIME ALLOWANCE
40
35
30
25
20
15
10
5
5
10
15
20
25
30
RESISTANCE (LBS)

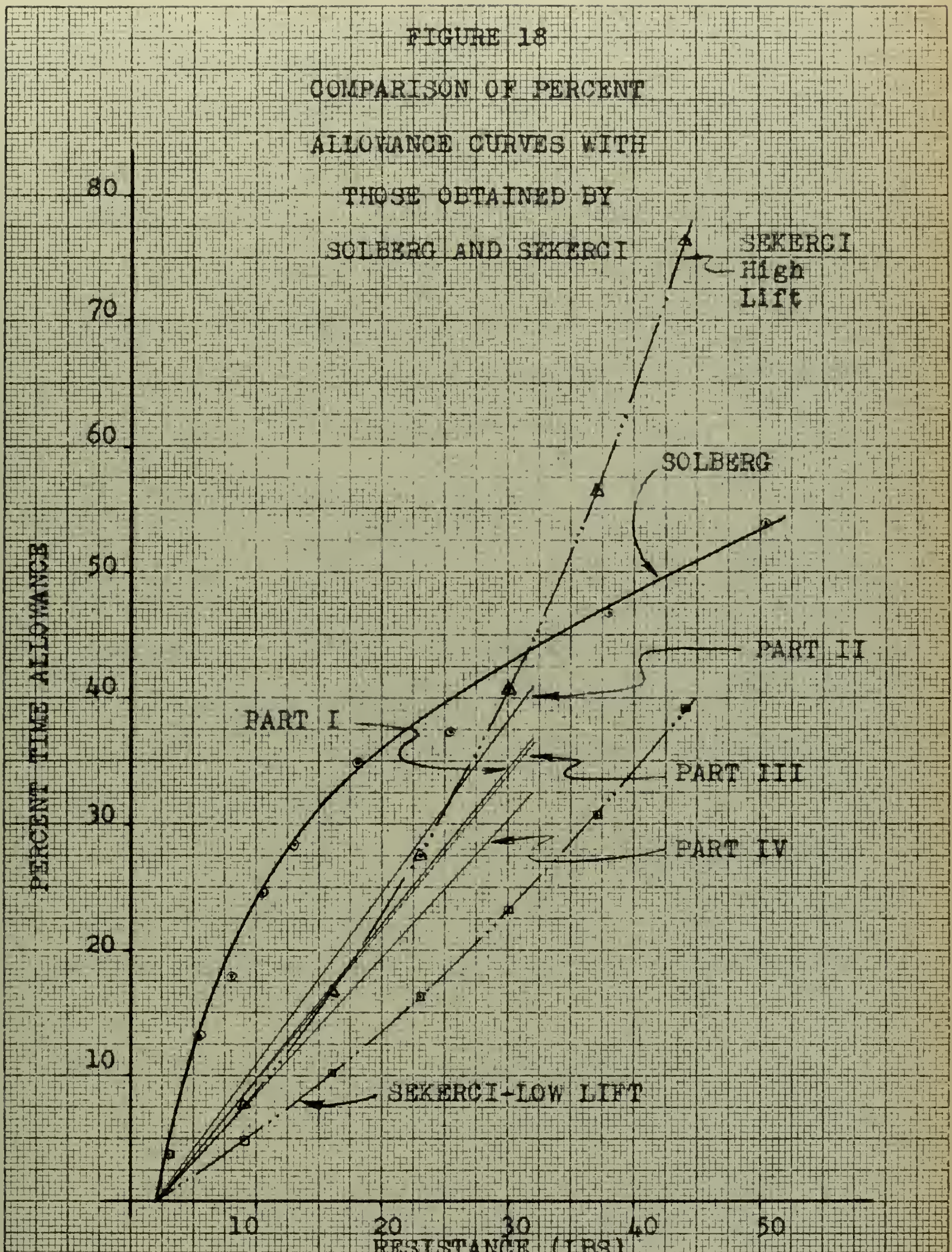
FIGURE 18
COMPARISON OF PERCENT
ALLOWANCE CURVES WITH
THOSE OBTAINED BY
SOLBERG AND SEKERCI
SEKERCI High Lift
SOLBERG
PART I
PART II
PART III
PART IV
SEKERCI-LOW LIFT
PERCENT TIME ALLOWANCE
RESISTANCE (LBS)
80
70
60
50
40
30
20
10
10
20
30
40
50

DISCUSSION OF RESULTS

The reduction of the data taken in this investigation consisted of the following steps:

1. To find the best fitting quadratic curve for each operator's performance (time per cycle versus resistance) on each part of the investigation.
2. To test whether a straight line would suffice to express the relationship in each case.
3. To determine if there were significant differences in position and slope of the curves for the sitting and standing parts of the experiment.
4. To determine if there were significant differences in position and slope of the curves for the pushing and pulling parts of the experiment.
5. To determine if there were any interactions between these basic methods which would make their effects other than additive.
6. To determine the equations of the curves relating work tempo with force applied in a horizontal plane.

The methods used in making these tests are described in Appendix B.

The statistical tests revealed that:

1. There is no significant curvature in the relationship between the time per cycle and the resistance, or, in other words, between work tempo and force applied in a horizontal plane.

2. This relationship exists for all four parts of this investigation, namely, standing and pushing, standing and pulling, sitting and pulling, and sitting and pushing.
3. There is a significant difference in time per cycle between performing the work standing up or sitting down with the latter being the more difficult.
4. There is a significant difference in the time per cycle between exerting the force by pushing or by pulling with the former being the more difficult.
5. There is no significant interaction between standing and sitting or pulling and pushing indicating that the effects of these changes in method can be considered additive.
6. The differences in the slopes of the curves for the four parts of the investigation are not significantly affected by the working conditions tested and, hence, the curves may be considered parallel.

A comparison of the percent allowance curves (Figure 18) with those developed by either Solberg[15] or Sekerci[16] reveals that these curves are not exactly like any of theirs. This indicates that overcoming a resistance in a horizontal plane is different from lifting weights or moving a weighted lever, and, therefore, that job difficulty can not be measured by the amount of resistance overcome alone. In other words, this difference indicates that an

allowance for job difficulty may not be determined for all jobs simply by knowing the amount of resistance overcome in the course of doing the job. The method used to overcome the resistance must be considered as well.

It might be well to note that the greatest discrepancy one could expect (in the range covered) by reading the wrong time allowance curve of these four is about eight percent (entering Figure 15 instead of 17). Assuming that they are accurate, it is not inconceivable that these four curves, although different, could be combined into one general curve for meeting resistances in a horizontal plane without suffering a large inaccuracy. An average curve should yield allowances within $\pm$ 4% of the correct value.

An analysis of the data shows remarkably constant times per cycle for each operator considering that the data were gathered in one period of nearly three hours in length. This is also true of the number of cycles, performed per minute (see Tables 7 through 16 in Appendix A). It is felt that this is due, in part at least, to the operators' starting a trifle slow but learning how better to pace themselves toward the end of the period when fatigue started to set in. To keep whatever effects are due to learning or fatigue from influencing the effects of working conditions, the order in which each part of the experiment and each resistance within each part were presented to the operators was randomized.

CONCLUSIONS

Under the conditions of this experiment and for the group of operators who performed the experiment, the following conclusions can be drawn:

1. Work tempo is, within the limits of experimental error, linearly related to force applied in a horizontal plane and decreases as the amount of force necessary to overcome resistance is increased.
2. The work tempo, and hence the difficulty entailed in overcoming a resistance in a horizontal plane, varies as the method employed to exert the force is changed. In particular, this investigation showed that:
   a. there is a significant difference in work tempo, or difficulty, between exerting a force horizontally while standing or while sitting, with the latter being the more difficult.
   b. there is a significant difference in work tempo, or difficulty, between exerting a force horizontally by pulling or by pushing with the latter being the more difficult.
   c. the interactions between sitting and standing or pulling and pushing are not significant and, hence, the effects of these changes in method may be considered additive.

3. For the four methods of overcoming resistance in a horizontal plane investigated in this experiment, sitting and pushing against the resistance was the most difficult and standing and pulling against the resistance proved the easiest.
4. A single allowance or adjustment curve applied universally to all types of work entailing the overcoming of resistance cannot be used without introducing an error into the time standard.
5. Allowances and/or adjustments to compensate for job difficulty are a function of the method employed in overcoming a resistance; hence, one universal value cannot suffice.

These findings agree in part with those made by Sekerci[17] and indicate a need for further investigation of this subject using different methods of overcoming resistance in oblique as well as horizontal and vertical planes.

APPENDIX A

ANALYSIS OF THE DATA FOR EACH OPERATOR

Tables 6 - 16, inclusive.

TABLE 6

STATISTICS ON OPERATORS

OPERATOR NUMBER

	1	2	3	4	5	6	7	8*	9	10
AGE	29	24	29	26	31	23	31	23	27	23
HEIGHT	73"	70½"	73½"	72½"	78"	76"	74"	66½"	69½"	72½"
WEIGHT	165#	190#	195#	185#	230#	215#	172#	175#	180#	205#
BUILD	SLENDER	HEAVY	MEDIUM	MEDIUM	HEAVY	HEAVY	SLENDER	MEDIUM	MEDIUM	HEAVY
ARM LENGTH	31½"	26"	31"	26"	33½"	29¼"	29¼"	24¼"	26¼"	28"
FOREARM LENGTH	20¼"	18½"	19½"	19"	20"	19½"	19½"	17"	18"	19"
LEG LENGTH	34½"	31½"	31½"	33"	36½"	35½"	37½"	29½"	32"	34½"
SHOULDER HEIGHT	62"	59"	61½"	61"	65"	63"	62"	55"	57"	60"
ELBOW HEIGHT	46½"	45"	47"	46"	49"	48½"	47"	42"	44½"	46"

*Nationality Turkish - All others U.S.

TABLE 7

DATA ON OPERATOR NO. 1

(Data are shown in the order in which the operator performed the experiment).

PART I (STANDING AND PUSHING)

RESISTANCE	4	32	2	24	16	8
CYCLES	30	30	29	30	30	30
TIME (SEC.)	20.830	25.990	16.470	19.550	19.345	18.820
CYCLES DONE IN MINUTE	96	64	96	93	87	93

PART II (STANDING AND PULLING)

RESISTANCE	2	32	8	24	4	16
CYCLES	30	20	30	30	40	30
TIME (SEC.)	16.565	20.780	16.497	18.650	21.985	18.250
CYCLES DONE IN MINUTE	105	76	99	92	107	97

PART III (SITTING AND PULLING)

RESISTANCE	2	24	32	16	4	8
CYCLES	40	30	30	30	30	30
TIME (SEC.)	24.005	19.510	21.815	18.973	16.970	17.042
CYCLES DONE IN MINUTE	94	89	78	91	104	102

PART IV (SITTING AND PUSHING)

RESISTANCE	32	8	16	24	4	2
CYCLES	30	30	30	30	30	30
TIME (SEC.)	29.340	20.677	22.400	23.355	20.620	17.700
CYCLES DONE IN MINUTE	61	86	79	78	85	102

TABLE 8

DATA ON OPERATOR NO. 2

(Data are shown in the order in which the operator performed the experiment).

PART I (STANDING AND PUSHING)

RESISTANCE	16	4	8	32	24	2
CYCLES	30	30	30	30	30	30
TIME (SEC.)	24.950	20.070	19.850	24.230	20.775	17.180
CYCLES DONE IN MINUTE	75	88	87	74	86	103

PART II (STANDING AND PULLING)

RESISTANCE	2	16	24	4	8	32
CYCLES	30	30	30	30	30	30
TIME (SEC.)	17.160	20.070	21.405	17.635	20.085	21.875
CYCLES DONE IN MINUTE	103	97	83	99	89	82

PART IV (SITTING AND PUSHING)

RESISTANCE	16	32	8	4	24	2
CYCLES	30	30	30	30	30	30
TIME (SEC.)	24.035	29.270	22.450	20.130	24.788	18.455
CYCLES DONE IN MINUTE	74	61	83	88	77	94

PART III (SITTING AND PULLING)

RESISTANCE	8	16	32	24	2	4
CYCLES	30	30	30	30	30	30
TIME (SEC.)	19.080	21.302	23.830	21.460	18.920	18.243
CYCLES DONE IN MINUTE	92	86	76	83	96	96

TABLE 9

DATA ON OPERATOR NO. 3

(Data are shown in the order in which the operator performed the experiment).

PART II (STANDING AND PULLING)

RESISTANCE	32	4	2	8	16	24
CYCLES	30	30	30	30	30	30
TIME (SEC.)	19.912	18.558	16.405	18.320	19.377	19.620
CYCLES DONE IN MINUTE	85	121	108	93	94	90

PART IV (SITTING AND PUSHING)

RESISTANCE	32	2	16	4	24	8
CYCLES	30	30	30	30	30	30
TIME (SEC.)	22.721	18.838	19.350	17.871	25.603	20.871
CYCLES DONE IN MINUTE	75	94	87	96	75	84

PART III (SITTING AND PULLING)

RESISTANCE	2	16	32	4	24	8
CYCLES	30	30	30	30	30	30
TIME (SEC.)	15.532	18.890	20.482	17.363	19.228	17.308
CYCLES DONE IN MINUTE	112	92	88	101	90	105

PART I (STANDING AND PUSHING)

RESISTANCE	8	2	4	32	24	16
CYCLES	30	30	30	30	30	30
TIME (SEC.)	17.062	16.349	16.163	24.869	19.957	20.256
CYCLES DONE IN MINUTE	100	109	106	77	87	87

TABLE 10

DATA ON OPERATOR NO. 4

(Data are shown in the order in which the operator performed the experiment).

PART I (STANDING AND PUSHING)

RESISTANCE	4	32	16	2	8	24
CYCLES	30	30	30	30	29	30
TIME (SEC.)	15.150	29.945	18.523	16.137	16.445	20.636
CYCLES DONE IN MINUTE	112	65	95	109	100	87

PART IV (SITTING AND PUSHING)

RESISTANCE	16	32	8	2	24	4
CYCLES	30	30	30	30	30	35
TIME (SEC.)	21.450	24.582	20.787	18.646	21.012	23.119
CYCLES DONE IN MINUTE	84	70	86	92	82	91

PART II (STANDING AND PULLING)

RESISTANCE	24	32	2	8	16	4
CYCLES	30	30	30	30	30	30
TIME (SEC.)	18.230	20.677	14.896	15.799	16.030	15.356
CYCLES DONE IN MINUTE	94	86	114	111	105	107

PART III (SITTING AND PULLING)

RESISTANCE	16	24	32	4	2	8
CYCLES	30	30	30	30	30	30
TIME (SEC.)	17.643	19.076	20.250	16.584	17.284	16.477
CYCLES DONE IN MINUTE	100	94	89	107	106	107

TABLE 11

DATA ON OPERATOR NO. 5

(Data are shown in the order in which the operator performed the experiment).

PART IV (SITTING AND PUSHING)

RESISTANCE	2	32	24	8	4	16
CYCLES	30	30	30	30	30	30
TIME (SEC.)	17.835	23.943	27.372	19.322	19.860	21.873
CYCLES DONE IN MINUTE	98	73	67	89	90	83

PART III (SITTING AND PULLING)

RESISTANCE	24	8	16	4	2	32
CYCLES	30	30	30	30	30	30
TIME (SEC.)	19.347	18.988	21.703	17.932	17.187	20.398
CYCLES DONE IN MINUTE	86	94	82	97	102	85

PART II (STANDING AND PULLING)

RESISTANCE	16	2	32	8	24	4
CYCLES	30	30	30	30	30	30
TIME (SEC.)	16.058	15.247	20.324	16.880	17.265	15.880
CYCLES DONE IN MINUTE	109	114	88	108	101	113

PART I (STANDING AND PUSHING)

RESISTANCE	32	16	8	24	4	2
CYCLES	30	30	30	30	30	30
TIME (SEC.)	23.947	22.695	19.191	22.674	17.944	14.776
CYCLES DONE IN MINUTE	66	78	90	79	96	119

TABLE 12

DATA ON OPERATOR No. 6

(Data are shown in the same order in which the operator performed the experiment).

PART III (SITTING AND PULLING)

RESISTANCE	32	24	8	2	16	4
CYCLES	30	30	30	30	30	30
TIME (SEC.)	26.903	24.897	23.676	19.759	21.238	19.013
CYCLES DONE IN MINUTE	65	73	74	91	85	91

PART II (STANDING AND PULLING)

RESISTANCE	32	2	4	24	8	16
CYCLES	30	30	30	30	35	30
TIME (SEC.)	21.381	17.175	18.102	19.389	20.138	17.918
CYCLES DONE IN MINUTE	82	103	105	90	99	101

PART I (STANDING AND PUSHING)

RESISTANCE	32	24	2	16	4	8
CYCLES	30	30	30	30	30	30
TIME (SEC.)	18.323	18.677	15.542	18.386	17.324	16.779
CYCLES DONE IN MINUTE	88	94	110	94	101	103

PART IV (SITTING AND PUSHING)

RESISTANCE	2	24	8	16	32	4
CYCLES	30	30	30	30	30	30
TIME (SEC.)	17.586	21.755	18.890	19.736	21.969	17.634
CYCLES DONE IN MINUTE	97	79	94	85	82	98

TABLE 13

DATA ON OPERATOR NO. 7

(Data are shown in the same order in which the operator performed the experiment).

PART I (STANDING AND PUSHING)

RESISTANCE	24	4	8	16	2	32
CYCLES	30	30	30	30	30	30
TIME (SEC.)	21.329	21.702	19.318	21.190	14.955	24.279
CYCLES DONE IN MINUTE	81	84	92	83	121	72

PART IV (SITTING AND PUSHING)

RESISTANCE	24	8	2	16	32	4
CYCLES	30	30	30	30	30	30
TIME (SEC.)	20.772	21.206	17.732	23.173	28.174	19.656
CYCLES DONE IN MINUTE	86	88	99	76	62	93

PART III (SITTING AND PULLING)

RESISTANCE	32	4	8	2	16	24
CYCLES	30	30	30	30	35	30
TIME (SEC.)	23.150	16.726	19.224	16.357	22.973	21.242
CYCLES DONE IN MINUTE	80	108	93	111	91	85

PART II (STANDING AND PULLING)

RESISTANCE	16	24	2	4	32	8
CYCLES	30	30	30	30	30	30
TIME (SEC.)	16.476	16.476	14.662	13.554	17.970	15.382
CYCLES DONE IN MINUTE	111	107	123	128	106	117

TABLE 14

DATA ON OPERATOR NO. 8

(Data are shown in the same order in which the operator performed the experiment).

PART II (STANDING AND PULLING)

RESISTANCE	8	24	4	2	16	32
CYCLES	30	30	30	30	30	30
TIME (SEC.)	20.784	20.843	15.601	14.433	23.651	21.425
CYCLES DONE IN MINUTE	87	83	107	114	76	84

PART IV (SITTING AND PUSHING)

RESISTANCE	4	24	8	32	2	16
CYCLES	30	30	30	30	30	30
TIME (SEC.)	20.204	30.028	26.299	37.377	20.866	28.333
CYCLES DONE IN MINUTE	85	60	67	50	83	62

PART I (STANDING AND PUSHING)

RESISTANCE	2	16	32	8	24	4
CYCLES	30	30	30	30	30	30
TIME (SEC.)	13.805	23.750	33.695	24.607	28.798	21.714
CYCLES DONE IN MINUTE	117	77	55	73	63	83

PART III (SITTING AND PULLING)

RESISTANCE	4	16	32	2	8	24
CYCLES	30	30	30	30	30	30
TIME (SEC.)	22.236	23.395	27.295	16.344	21.127	25.361
CYCLES DONE IN MINUTE	83	76	65	103	84	76

TABLE 15

DATA ON OPERATOR NO. 9

(Data are shown in the same order in which the operator performed the experiment).

PART II (STANDING AND PULLING)

RESISTANCE	24	8	16	4	32	2
CYCLES	30	30	30	30	30	30
TIME (SEC.)	15.716	15.749	18.058	15.804	20.439	14.088
CYCLES DONE IN MINUTE	103	112	99	112	88	123

PART IV (SITTING AND PUSHING)

RESISTANCE	24	32	2	8	4	16
CYCLES	30	30	30	30	30	32
TIME (SEC.)	21.764	24.024	17.866	26.946	18.624	21.994
CYCLES DONE IN MINUTE	80	72	98	89	92	81

PART III (SITTING AND PULLING)

RESISTANCE	2	24	16	4	8	32
CYCLES	30	30	30	30	30	30
TIME (SEC.)	16.660	20.567	19.117	16.659	17.440	25.794
CYCLES DONE IN MINUTE	104	86	91	104	101	72

PART I (STANDING AND PUSHING)

RESISTANCE	4	16	24	8	32	2
CYCLES	30	30	30	30	30	30
TIME (SEC.)	14.658	19.152	18.223	18.116	21.786	15.351
CYCLES DONE IN MINUTE	117	95	92	98	82	115

TABLE 16

DATA ON OPERATOR NO. 10

(Data are shown in the same order in which the operator performed the experiment).

PART IV (SITTING AND PUSHING)

RESISTANCE	4	24	2	8	32	16
CYCLES	30	30	30	30	30	38
TIME (SEC.)	16.856	20.129	17.108	18.091	20.022	23.390
CYCLES DONE IN MINUTE	103	88	101	95	87	96

PART III (SITTING AND PULLING)

RESISTANCE	16	2	24	8	32	4
CYCLES	30	30	30	30	30	30
TIME (SEC.)	18.814	17.027	20.698	18.483	22.646	18.689
CYCLES DONE IN MINUTE	95	104	85	95	80	98

PART I (STANDING AND PUSHING)

RESISTANCE	24	8	2	32	4	16
CYCLES	30	30	30	30	30	30
TIME (SEC.)	17.513	16.524	15.153	18.875	14.833	16.703
CYCLES DONE IN MINUTE	99	106	114	94	116	105

PART II (STANDING AND PULLING)

RESISTANCE	32	24	4	16	8	2
CYCLES	30	30	30	30	30	30
TIME (SEC.)	22.939	16.133	15.835	17.155	16.401	14.511
CYCLES DONE IN MINUTE	87	106	110	104	108	120

APPENDIX B

STATISTICAL ANALYSIS

STATISTICAL ANALYSIS

The data shown in Tables 1 through 4 were reduced in the following fashion. A general second order curve was fitted to all forty different sets of data (ten operators and four parts) by use of orthogonal polynomials. This yielded forty different equations of the type,

$$\hat{\alpha} P_0(x) + \hat{\beta} P_1(x) + \hat{\gamma} P_2(x) = 0$$

(where $P_0(x)$, $P_1(x)$, and $P_2(x)$ are orthogonal polynomials of degrees 0, 1, and 2 respectively over the values 2, 4, 8, 16, 24, and 32).

Next a test was performed to see if a straight line would suffice instead of a quadratic curve. This was done by observing how much of the variation about the fitted line was removed by the use of the second degree polynomials as compared to the total amount of variation present. This comparison is made by means of the ratio, $\Sigma\hat{\gamma}^2/\Sigma\hat{\sigma}^2$ which has the F distribution with degrees of freedom (40,120). If this ratio is less than 1.49 it can be concluded, at the five percent level of significance, that these data do not show that the second order coefficients are different from zero. For the data collected in this investigation,

$$\frac{\Sigma\hat{\gamma}^2}{\Sigma\hat{\sigma}^2} = 1.3329 < 1.49$$

indicating that the individual curves could be considered as straight lines (i.e. the coefficients of the quadratic terms equal to zero).

The next step was to perform a mixed model analysis of variance in which the differences among the non-random effects of sitting, standing, pulling, or pushing are tested against an experimental error which includes the error due to the differences among operators. This consisted of three parts essentially, namely, a test to see whether in exerting a force horizontally 1.) there is any difference between sitting and standing, 2.) there is any difference between pushing and pulling, and 3.) there are any interactions among these which might make whatever differences found non-additive. This analysis was performed on both the $\hat{\alpha}$'s and the $\hat{\beta}$'s. The mechanics of the analysis will not be discussed here. The results of these analyses are shown in Table 17. The forty values of $\hat{\alpha}$ and the forty values of $\hat{\beta}$ are shown in Tables 18 and 19 respectively.

The fitted curves (Figures 10 through 13) were drawn in the following manner. The values of both $\hat{\alpha}$ and $\hat{\beta}$ were averaged across men for each part of the experiment (see Tables 18 and 19). Since there was negligible difference between the $\hat{\beta}$'s for each part (see Table 17), these values were averaged across parts giving one grand mean $\hat{\beta}$ for the experiment.

The values, $\hat{\alpha}$, in this experiment are not related to the intercept of the line directly, but rather to the value of the function at the mean resistance (14.333 pounds). The height of each of the curves at this point was found

by multiplying the appropriate value of $\hat{\alpha}$ by $1/\sqrt{6}$ which is equal to 1/2.4495. The value of the slope of each line was gotten by multiplying the average $\hat{\beta}$ by $1/\sqrt{707.33}$ which is equal to 1/26.5957. The resulting equations for the curves, listed in Table 23, were derived by noting that the point $(14.333, \hat{\alpha}/\sqrt{6})$ is on the curve. Therefore the curves are of the form,

$$y - \frac{\hat{\alpha}}{2.4495} = \frac{\hat{\beta}}{26.5957}(x - 14.333) .$$

TABLE 17

RESULTS OF THE ANALYSIS OF VARIANCE

The analysis of variance was run to see if the differences between sitting and standing, the differences between pushing and pulling, and the extent of their interaction were significant.

	Computed value of the F-ratio for		Significant points		Degrees of Freedom
	$\hat{\alpha}$	$\hat{\beta}$	$F_{.05}$	$F_{.01}$	
Difference between sitting & standing	38.04	< 1	5.12	10.56	(1,9)
Difference between pushing & pulling	9.99	3.25	5.12	10.56	(1,9)
Interaction	< 1	< 1	5.12	10.56	(1,9)

TABLE 18

COMPUTED VALUES OF $\hat{\alpha}$

	SITTING		STANDING	
MAN	PUSHING	PULLING	PUSHING	PULLING
1	1.824748	1.528377	1.654383	1.600600
2	1.893272	1.671557	1.728981	1.608896
3	1.704478	1.466997	1.560253	1.526728
4	1.718624	1.460347	1.597636	1.374256
5	1.778661	1.579294	1.649680	1.383319
6	1.599910	1.843715	1.429271	1.513586
7	1.778763	1.583854	1.670716	1.286246
8	2.260412	1.847418	1.991811	1.588573
9	1.766932	1.581772	1.459967	1.358828
10	1.573043	1.583401	1.355383	1.401286
MEAN	1.7898843	1.6146732	1.6098081	1.4642318

TABLE 19

COMPUTED VALUES OF $\hat{\beta}$

	SITTING		STANDING	
MAN	PUSHING	PULLING	PUSHING	PULLING
1	.274620	.125686	.170214	.353698
2	.274444	.151965	.157266	.132537
3	.165392	.111473	.237276	.079729
4	.133810	.103606	.371064	.157641
5	.217228	.088812	.239223	.117399
6	.141077	.202092	.072601	.108817
7	.226915	.189021	.174687	.107650
8	.433829	.252176	.454655	.186189
9	.107437	.248536	.172249	.133233
10	.109710	.139544	.107500	.179636
MEAN	.2084462	.1612911	.2156735	.1556529

MEAN OF MEANS .1852659

TABLE 20

EQUATIONS OF FITTED CURVES

PART I (STANDING AND PUSHING):

$$y - \frac{1.6098081}{2.4495} = \frac{0.1852659}{26.5957} (x - 14.333)$$

$$y - 0.6572 = 0.006966 (x - 14.333)$$

PART II (STANDING AND PULLING):

$$y - \frac{1.4642318}{2.4495} = \frac{0.1852659}{26.5957} (x - 14.333)$$

$$y - 0.5978 = 0.006966 (x - 14.333)$$

PART III (SITTING AND PULLING):

$$y - \frac{1.6146732}{2.4495} = \frac{0.1852659}{26.5957} (x - 14.333)$$

$$y - 0.6591 = 0.006966 (x - 14.333)$$

PART IV (SITTING AND PUSHING):

$$y - \frac{1.7898843}{2.4495} = \frac{0.1852659}{26.5957} (x - 14.333)$$

$$y - 0.7301 = 0.006966 (x - 14.333)$$

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